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CAVITATION DYNAMICS: IV. COLLAPSE OF TRANSIENT CAVITIES.(U)
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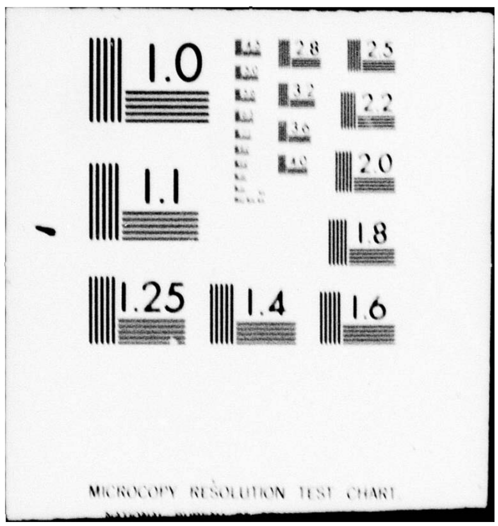
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CAVITATION DYNAMICS:

IV. COLLAPSE OF TRANSIENT CAVITIES

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by

(10) H. G./Flynn

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Calculations have been made of the maximum pressures and temperatures that may occur in collapsing argon bubbles in water through use of a previously developed mathematical formulation (J. Acoust. Soc. 57, 1379-1396 (1975)). Equation-of-state data valid for water and argon at high pressures were introduced into the formulation in an effort to determine upper bounds of such maximum pressures and temperatures. The limitation

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imposed on pressures and temperatures in collapsing bubbles by growing perturbations on spherical interfaces was also studied.

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CAVITATION DYNAMICS: IV. COLLAPSE OF TRANSIENT CAVITIES

by

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The growth and violent collapse of small bubbles in liquids under the influence of an acoustic pressure field gives rise to a host of phenomena that may be summed up in the phrase, "cavitation activity". This term includes the erosion of solid surfaces, the radiation of noise with a frequency spectrum extending into the MHz region, the emission of light, the initiation of chemical reactions and the destruction of living cells. The generation of such phenomena in cavitation zones has usually been ascribed to the occurrence of high pressures and temperatures within collapsing bubbles and the subsequent radiation of intense shock waves.

This paper reports calculations made with the aim of placing upper bounds on the pressures and temperatures that might occur in a cavitation event, a term used here to denote the growth of a cavity from a small pre-existing "seed" of gas in a liquid to some maximum radius R_o, its subsequent collapse to a minimum radius, R_m, and its possible rebound. The paper is the fourth in a sequence on cavitation dynamics.[1,2,3] The calculations have been carried out by use of a mathematical formulation derived in the first paper of the sequence, hereinafter referred to as CD:I. This formulation, shown in Table I of CD:I, consists of a set of non-linear differential, integral and algebraic equations that have been programmed for simultaneous solution on a digital computer.

The set of equations enable one to take into account the compressibility and shear viscosity of the liquid, the transfer of heat across the cavity interface and the surface tension of

the interface. Solutions of the set of equations predict the radius-time curve of the cavity, the pressure, temperature and entropy of the cavity contents, the velocity and acceleration of the interface, the temperature in the liquid at the interface and the work done by or on the cavity as it expands and contracts. Limitations on the usefulness of such predictions include the assumptions that the speed of sound in the liquid is constant, that the cavity retains its spherical shape throughout the motion, that the amount of gas and the vapor pressure in the cavity both remain constant, and that the bubble has no translation motion.

The system of notation adopted in CD:I will be employed here. In this notation, an asterisk (*) denotes a quantity in some convenient set of units. Thus, R_n^* is the equilibrium radius of a cavity in centimeters, while $R = R^*/R_n^*$ is the non-dimensional radius of the cavity of radius R^* in centimeters. The non-dimensional pressure is $p = p^*/p_{\ell n}^*$ where p^* is the pressure in bars and $p_{\ell n}^*$ is the equilibrium pressure of the liquid in bars.

In this formulation, the equation of motion for the cavity interface (Eq. 20 in CD:I) is a modification of a non-linear ordinary differential equation derived by Conyers Herring[4]. In these calculations, this equation is used to predict the motion of the cavity during the growth phase and in the collapse phase until mechanical energy is transferred to the cavity contents so rapidly that the effect of heat conduction is negligible. The compression of the cavity contents is then taken to be adiabatic during the remainder of the collapse. Once this transition to an adiabatic regime is made, the solution of the modified Herring equation is continued through use of an ordinary differential equation derived by Gilmore[5] and shown as Eq. 13 in CD:I. Gilmore derived his equation through use of the Kirkwood-Bethe invariant.[6]

The pressure and temperature in a collapsing bubble in a liquid are essentially inaccessible to observation when the bubble contracts to some small fraction of its equilibrium radius, R_n^*. Such bubbles remain at their minimum volume for a time interval less than a nanosecond and even their minimum radii are usually

impossible to determine. Faced with such obstacles, experimenters have resorted to indirect evidence of conditions within collapsing bubbles, and have relied heavily on theoretical investigations for guidance.

The problem of a collapsing cavity has provided a fertile field of study ever since the time of Lord Rayleigh[7]. Much of this earlier work has been summarized elsewhere[8]. Of this long sequence of investigations, two are of particular relevance to the work reported here.

Hickling and Plesset[9] obtained detailed descriptions of the collapse of an air-filled cavity in water from numerical equations of compressible flow in both characteristic and Lagrangian forms. Their solutions were carried beyond the final collapse point into the region where the liquid rebounds and generates a shock wave. One result of importance to the present work is that they found predictions of cavity collapse of the Gilmore equation were "surprisingly good" when compared to the exact numerical solutions. A second result is the prediction that in a cavity in which the gas pressure was intially 10^{-4} atm at its maximum radius, R_o, the final pressure was 2×10^5 atmospheres.

Ivany and Hammitt[10] similarly obtained numerical solutions for collapse of an air-filled cavity in a compressible liquid, but included the effect of viscosity as well. They determined the radius-time curve of the cavity interface by use of the Gilmore equation and then determined the pressure field in the surrounding liquid by integrating the Kirkwood-Bethe invariant along outgoing characteristics. In one example, their numerical analysis showed that in a cavity in which the gas pressure was intially 10^{-4} atm. at its maximum radius, R_o, the final pressure was 5.82×10^5 atm.

In both the Hickling-Plesset and Ivany-Hammitt calculations, it was assumed that the gas was ideal with a constant specific heat ratio, γ, and that the liquid could be described by a modified Tait equation of state introduced by Kirkwood and Richardson[12,13]. In both numerical results quoted above, the compression of the gas was assumed to be adiabatic. These assumptions are almost invariably made by investigators (for example,

by Esipov and Naugol'nykh[14]). The limitations on the ideal gas equation are obvious and the modified Tait equation is at best useful only below 80 kilobars.

Experimentalists have produced widely varying estimates of the maximum pressures that occur in collapsing cavities. Most pressure measurements have been made in experiments where bubbles have collapsed on or near solid surfaces. Such bubbles almost always deform and often form high-speed jets that impinge on the surfaces. In experiments of this class, Jones and Edwards[15] concluded that a peak pressure of 10,000 bars occurred. Naudé and Ellis[16] inferred a collapse speed exceeding the speed of sound in the liquid and pressure estimates agreeing with those of Jones and Edwards. Sutton[17] reported cavitation-induced stresses of 13,000 bars in the surface of a photoelastic solid. The most thorough study of a bubble collapsing far from a surface has been the work of Radek[18] who came to the conclusion that a peak pressure of 10^5 bars was reached in a bubble under observation. This number is a factor of 10 higher than the peak pressure reported by Radek and Kuttruff[19] two years earlier.

Measurement of the minimum size of a collapsed cavity has generally eluded investigators and few attempts have been made to determine maximum temperature in a collapsing bubble. The few that attempted to determine the maximum temperature used the phenomenon of sonoluminescence, a very faint glow sometimes observed in cavitating liquids, with a spectra resembling that of a black body at 6000 K to 11,000 K.[20]

The exact solutions of Hickling and Plesset and the calculations of Ivany and Hammitt show that the formulation of CD:I can be relied upon to describe a cavity during its growth and most of the collapse phase, at least so long as pressure in the cavity is less than about 3 kilobars. At the same time, the work of Hickling and Plesset established the usefulness of the Gilmore equation when the pressure is higher.

The validity of the mathematical formulation having been established, the next step was to find equations of state for both the gas in the cavity and for the water surrounding it that are

reliable at very high pressures and temperatures.

In the equation of motion (Eq. 20 of Table I), the speed of sound in the liquid is assumed to be a constant; that is, the variation of pressure is a linear function of a variation in the density of the liquid. This assumption has been found to be adequate so long as the pressure is less than 3 kilobars.

In the Gilmore equation (Eq. 13 in CD:I), the speed of sound, A, the enthalpy, H, and the rate of change of enthalpy, $\frac{dH}{dt} = U(dH/dR)$, appear as functions. Because the Gilmore equation is used here only during the adiabatic phase of collapse, these are functions only of the pressure, P, at the interface and hence of the radius, R, of the cavity. Values of A, H, and dH/dR have been calculated at selected values of the pressure, and relations of the form:

$$A = A_o/R^n \quad , H = H_o/R^b \quad , \text{ and } dH/dR = H_1/R^q$$

where A_o, H_o, H_1, n, b, and q are constants, are then used to interpolate between these selected pressures.

The relationof P to the radius, R, of the cavity, is found through an adiabatic curve for argon constructed for these calculations. This curve furnishes a p-ρ curve where $\rho = \rho_c$ where ρ_c is the density of the gas in the cavity. This density, ρ_c, is then related to the radius, R, through $\rho_c = \rho_{cn}/R^3$ (Eq. 26 of CD:I). In this manner, a table of p-R is constructed for the selected values of p and hence A, H and dH/dR can be calculated for a set of values of R and interpolation between such values of R carried out during the computations as noted above.

The equation-of-state data for the liquid is the Hugoniot curve established by the Rice-Walsh equation of state for water[21] from shock wave experiments. The Hugoniot is the locus of states that can be reached through a shock transition from some initial state; it lies above the adiabatic curve which is the locus of states that can be reached through an adiabatic transition from an initial state. The Rice-Walsh equation is generally regarded as furnishing the most reliable data on water even when extended into the megabar region[22,23]. Rice and Walsh constructed tables

of the sound speed, A, and the entropy, H, along the Hugoniot for water up to 450 kilobars. The sound speed, A, which is probably the most important parameter of the liquid in this context, deviates from that calculated by the use of the modified Tait equation at pressures as low as 20 kilobars.

An adiabatic curve for argon has been constructed for a value of the non-dimensional entropy, S/R = 21, which was found to be an average for the terminal entropy within collapsing cavities studied in this investigation. For pressures less than 10^4 bars, the tables of Hilsenrath, Messina and Klein[24] were used. These tables provide the thermodynamic properties of argon in chemical equilibrium with second virial corrections for gas imperfection. In order to extend the curve to higher pressures, values of p and ρ for S/R = 21 were calculated using the ideal-gas functions computed by Woolley[25], corrected for deviations due to gas imperfection through use of the Lennard-Jones and Devonshire (L-J-D) equation of state. These corrections were taken from the tables of Wentorf, Buehler, Hirschfelder and Curtiss[26].

The use of the L-J-D equation-of-state parameters for argon essentially assumed that ionization had little effect on the pressure-density relationship. Obviously, some check on the plausibility of this assumption was needed. At much higher pressures and temperatures, the gas would be totally ionized and the Thomas-Fermi-Dirac equation of state would provide the most reliable description of argon in that state. Through use of the results of Geiger, Hornberg and Schramm[27] for totally ionized argon based on the T-F-D equation of state, values of p and ρ at S/R=21 were calculated for a temperature of 1.755×10^5 K. The values of 1.52×10^9 bars for the pressure and of 91.62 g cm^{-3} were found to lie on the straight line through the L-J-D points of the argon adiabat when extended into the megabar region. The adiabatic curve shown in Figure 1 can therefore be regarded as a reasonable model for argon into the megabar region.

For the calculations of collapsing cavities reported here, it is assumed that a small, pre-existing seed of argon and water vapor is caused to expand by a negative pressure pulse of

specified amplitude and a width of 1 microsecond. The acoustic pressure amplitude is varied from 10 to 50 bars, and the width of the pulse is such that the applied acoustic pressure is zero when the cavity has expanded to its maximum radius, R_o. Under such a pressure pulse, the cavity reaches a maximum radius given by the following:

Pressure amplitude (bars)	Maximum radius, R_o
10	10.628
20	19.470
30	27.916
50	46.274

At R_o, the cavity starts to contract under the ambient pressure of 1 bar. As the cavity accelerates inward, the work done on the cavity contents increases so rapidly that the effect of heat conduction becomes negligible, the entropy of the cavity contents becomes constant and the compression is adiabatic. This transition occurs when R is close to its initial value. The solution is then continued by means of the Gilmore equation.

Solutions obtained with the mathematical formulation of CD:I in which the pressure is a linear function of the density in the liquid and argon is taken to be an ideal gas will be referred to as "ideal" model solutions while those obtained by use of the Rice-Walsh Hugoniot and the adiabatic curve for argon shown in Fig. 1 will be referred to as "realistic" model solutions.

Fig. 2 shows the maximum pressures obtained as a function of maximum radius, R_o. One curve shows the values obtained by use of the "realistic" model while the other shows values calculated by use of the "ideal" model even in the region of adiabatic compression. For the "realistic" model, the lowest pressure is 5.71×10^4 bars and the highest pressure is 1.15×10^6 bars.

In Fig. 3, the maximum temperatures in a collapsing cavity are shown as a function of maximum radius, R_o. The "realistic" model predicts temperatures ranging from 2.50×10^4 K to 3.88×10^4 K, while the "ideal" model predicts temperatures in a range from

1.46×10^4 K to 4.98×10^4 K. It is noteworthy that the two curves obtained by use of the two models cross. This intersection reflects the fact that the temperature-density curve for an ideal gas intersects the adiabatic temperature-density curve for the adiabatic curve shown in Fig. 1 in the same manner. In other words, the temperature in an ideal gas would be higher at the higher density.

The calculations reported here were made in anticipation that the results would provide upper bounds on pressures and temperatures found in collapsing cavities of a given initial radius and a given maximum radius. As noted earlier, there were assumptions made that would tend to make the maximum pressures and temperatures in a bubble lower than these upper bounds. The effects of a rise in temperature at the interface, the evaporation and condensation of vapor and the diffusion of gas across the interface will not be examined here. One factor that will be examined here is the assumption that the cavity remains spherical throughout its motion.

Birkhoff[28,29] showed conclusively that the interface of a collapsing spherical cavity would remain stable only when its acceleration, dU/dt, is negative and the function, R^5(dU/dt) is a decreasing function; that is, the inward acceleration must increase faster than R^{-5}. In the motions studied here, the acceleration did not increase so rapidly and hence the interfaces were presumably unstable in the sense that a small perturbation of the interface would grow in magnitude.

It therefore seemed worthwhile to investigate this problem of instability in more detail. The starting point is an expansion in the form of an infinite series of Legendre functions of the form:

$$r(t) = R(t) + \sum_n r_n(t)\, P_n(\cos\theta)$$

where r(t) is the radius of the perturbed cavity, R(t) is the radius of the unperturbed spherical cavity, $P_n(\cos\theta)$ are Legendre functions of order n and $r_n(t)$ are the time dependent perturbation amplitudes. While the equations of Birkhoff probably would be adequate for this investigation, an equation derived by Pennington[30]

was used to calculate the change in the perturbation amplitudes, $r_n(t)$, as a cavity collapsed. Pennington's equation took into account both viscosity and surface tension, both of which are factors that tend to inhibit the growth of perturbations. The Pennington equation has the following form:

$$R\,\dot{u}_n + u_n\{3U + 2(n+1)(n+2)\mu/\rho_{\ell n}R\} + (n-1)r_n$$
$$\{(n+1)(n+2)\sigma/\rho_{\ell n}R - \dot{U} + 2(n+1)\mu U/\rho_{\ell n}R^2\} = 0$$

where R, U, and $\dot{U}$ are the radius, velocity and acceleration of the unperturbed spherical interface and μ and σ are the coefficients of viscosity and surface tension, r_n is the perturbation amplitude, u_n is the rate of change of r_n and $\dot{u}_n$ is the rate of change of u_n. In all cases, it was assumed that the initial values of r_n and u_n were 10^{-5} in magnitude. The functions R, U and $\dot{U} = dU/dt$ were calculated simultaneously with the perturbation amplitude, r_n, and fed into the Pennington equation during the collapse calculation.

Fig. 4 shows the results of the calculation of the perturbation amplitude, r_2, for the same conditions in which the cavity expanded to $R_o = 46.274$ and then collapsed to a maximum pressure of more than a megabar.

The most important result of the calculation of r_2 is its strong dependence on initial conditions. Thus, if the radius, R_i, at which the perturbation appears on the surface of the sphere is its maximum radius, R_o, the perturbation amplitude r_2 grows rapidly to a value slightly less than 10^{-1} and then oscillates with ever increasing maxima and minima. However, if the perturbation appears when R has contracted to about 0.1 of its initial value, the perturbation increases much less rapidly. When the radius, R_i, at which the perturbation appears, is 0.01 of R_o, the perturbation amplitude actually decreases initially before it starts to oscillate. The inference is that the chance of a collapsing cavity attaining a very high pressure increases when the onset of a perturbation is delayed.

Benjamin and Ellis[31], who carried out experiments on collapsing cavities both in free fall (i.e., in zero gravity) and under the influence of gravity, concluded that in acoustic cavitation as well as hydraulic cavitation the rate of formation of "destructive" bubbles must be very small in comparison with the total rate of formation of cavitation bubbles. They quoted the observation of R. T. Knapp that only one out of 30,000 transient cavities in hydraulic cavitation caused erosion of an aluminum test section. High speed photographs taken by Benjamin and Ellis showed that, far from the liquid boundary, a cavity maintained its spherical shape during collapse under gravity but that on rebound a high speed jet had developed during the interval of minimum size. A similar cavity observed under zero gravity conditions showed no vestige of this behavior. The calculations of r_2 shown in Fig. 4 are consistent with these remarks of Benjamin and Ellis.

Whether such high pressures and temperatures as obtained in these calculations occur in collapsing bubbles is at present an unresolved question. The solutions obtained with the "realistic" model make it clear that the compressibility of the liquid, viscosity, surface tension and heat conduction in themselves do not prevent their occurrence. The deformation of a cavity interface depends strongly on the stage of collapse at which a perturbation appears. Bubbles have been almost universally observed to be smooth spheres at their maximum radius and deform only as they contract. Hence it is probable that perturbations appear on bubbles far from a solid surface in a random manner. In a cloud of cavitation events, the survival of a bubble until its internal pressure and temperature approach the upper bounds reported here would appear to be a statistical phenomenon.

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FIGURES

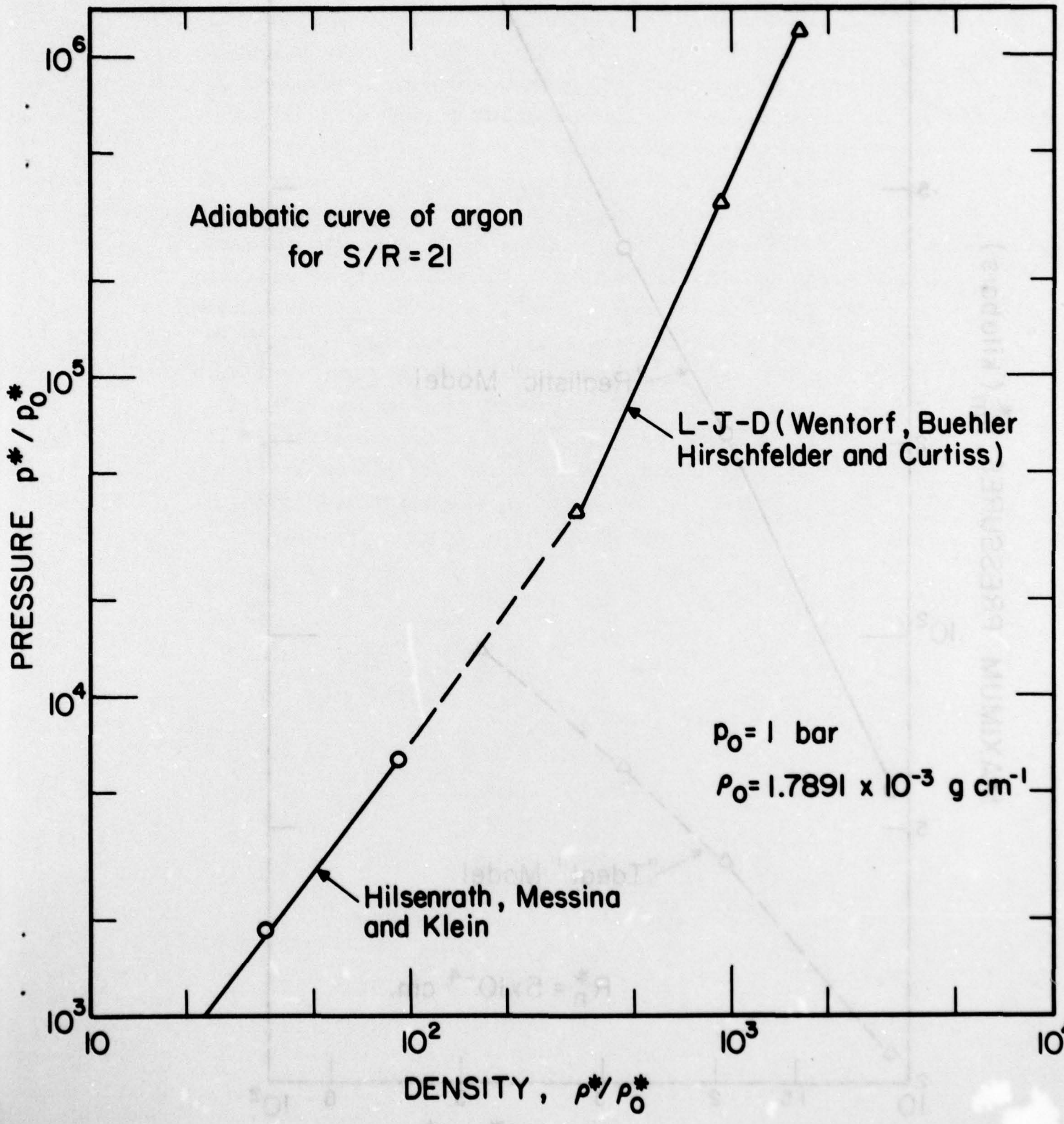

Fig. 1 Equation of state for argon

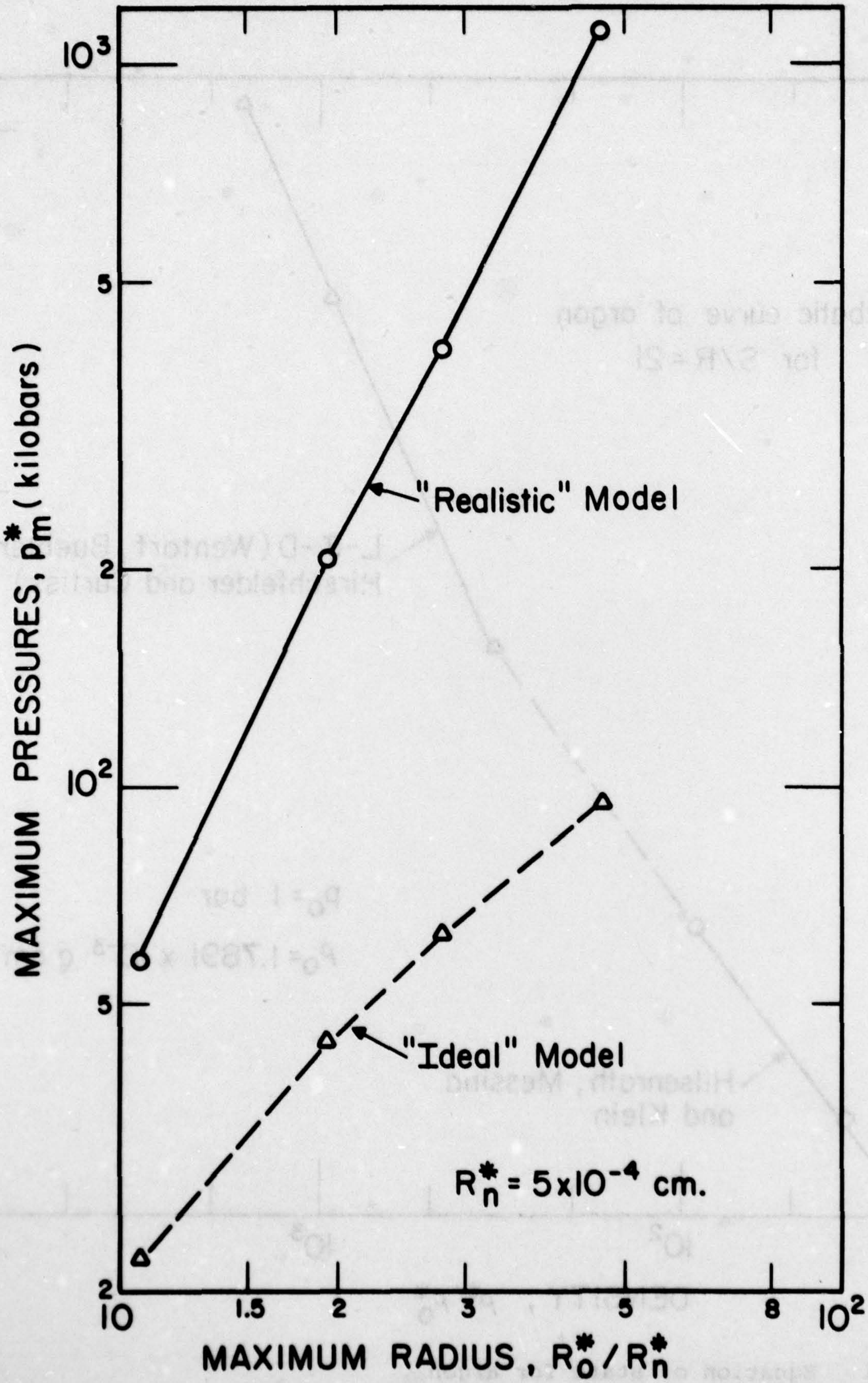

Fig. 2 Maximum pressure in a collapsing cavity

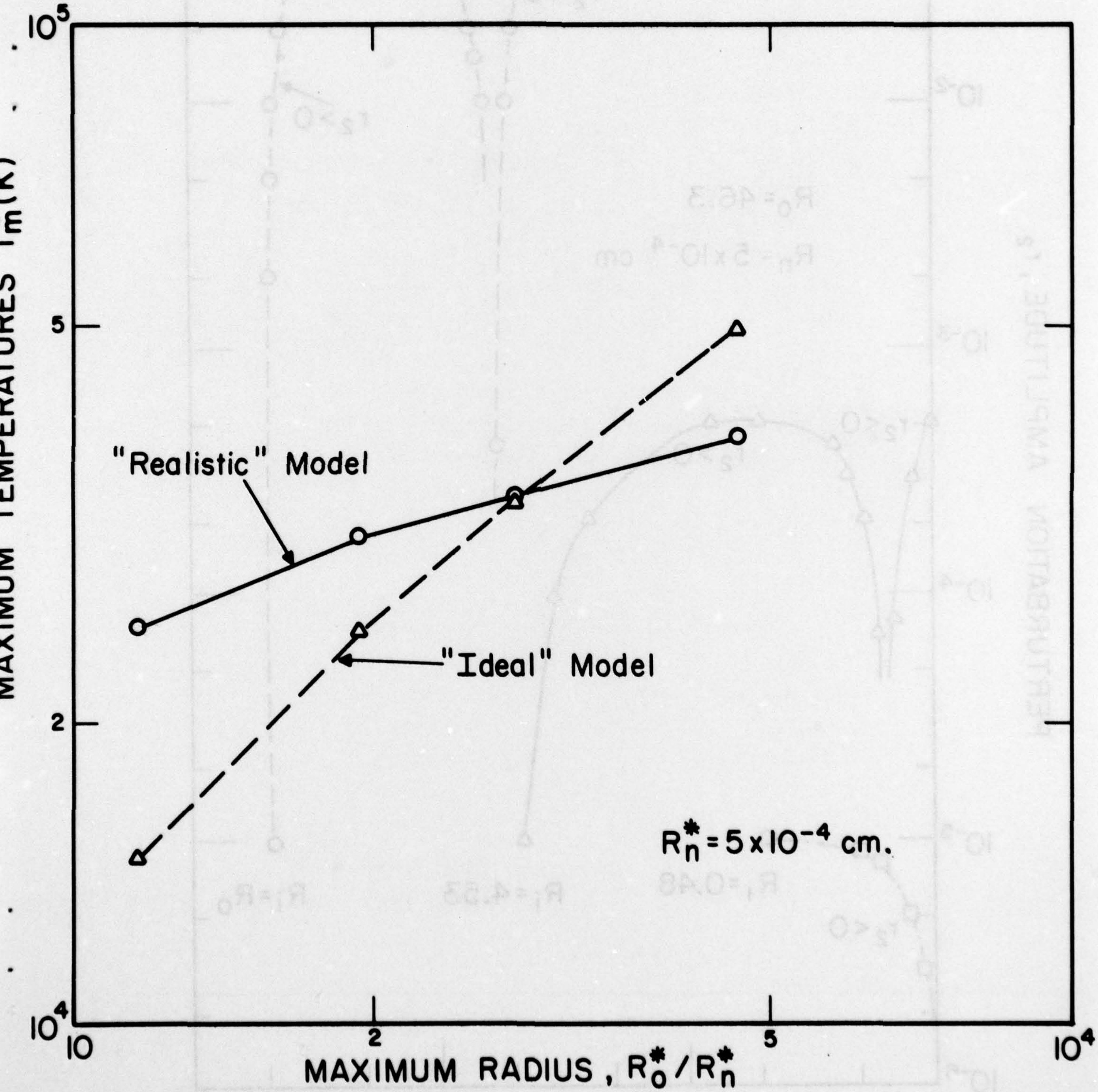

Fig. 3 Maximum temperature in a collapsing cavity

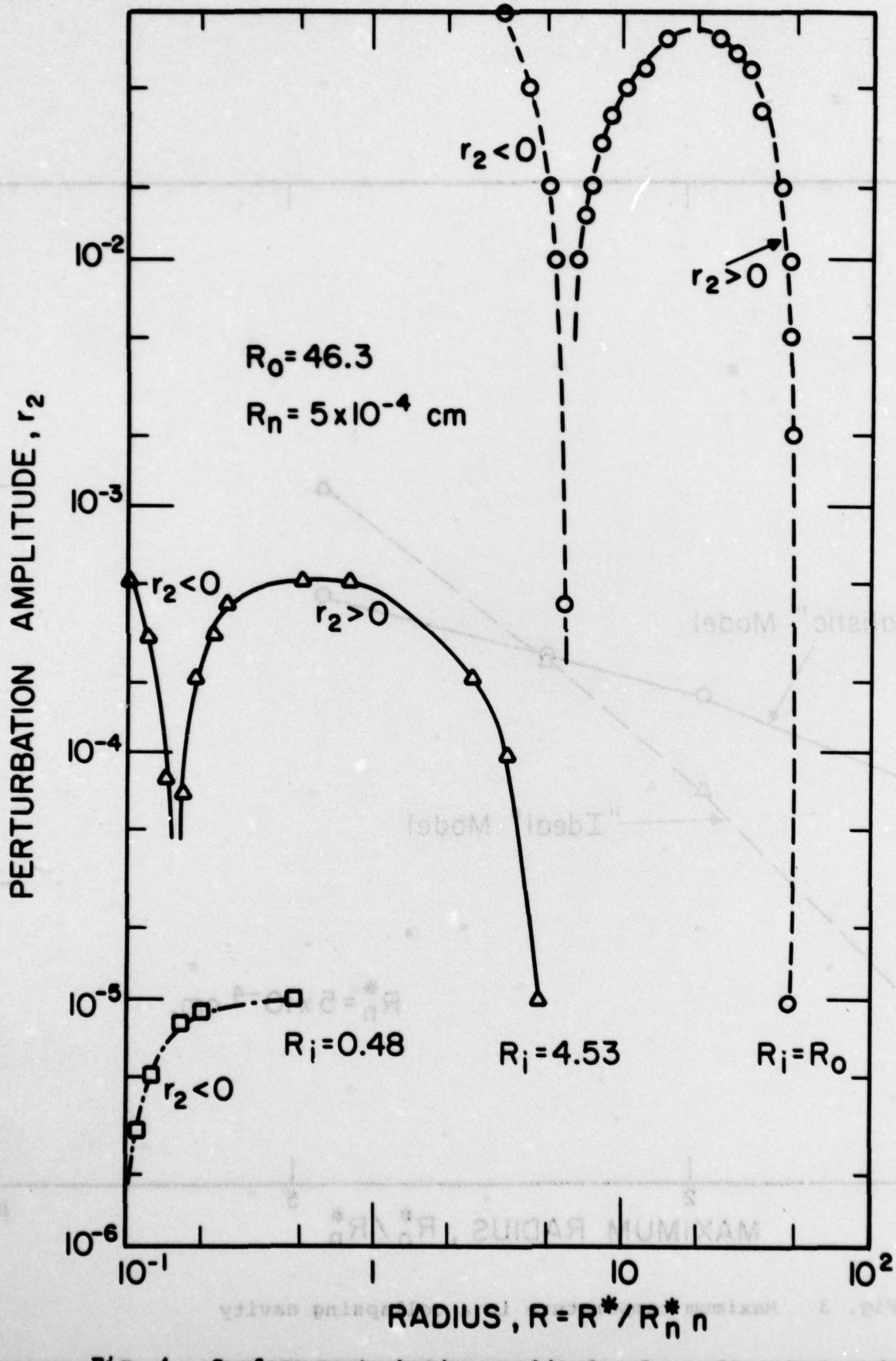

Fig. 4 Surface perturbation amplitude of a collapsing cavity